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Waterways Experiment Station

Use of Large Quantities of Fly Ash in Concrete

by Toy S. Poole

Prepared for Headquarters, U.S. Army Corps of Engineers

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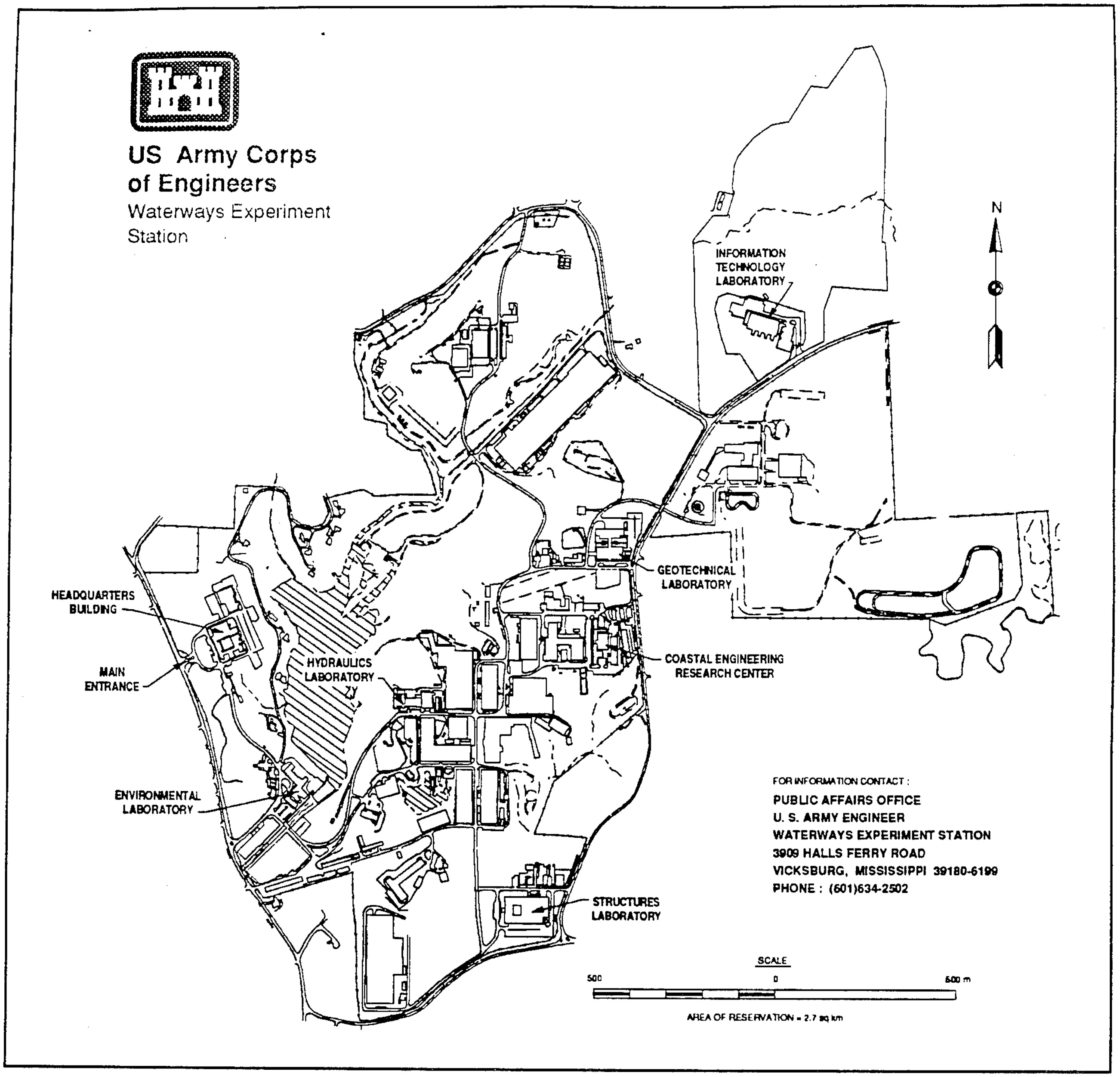

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Contents

Preface

This report reviews some of the literature pertaining to the use of large amounts of fly ash in concrete. The report was prepared by the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), for Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Investigational Study Work Unit 32423, "Optimizing Cement and Pozzolan Quantities in Concrete." Dr. Tony Liu was the HQUSACE Technical Monitor.

The report was written by Dr. Toy S. Poole, Concrete Technology Division (CTD), SL. The work was conducted under the supervision of Dr. Lillian D. Wakeley, Acting Chief, Materials Engineering Branch, Mr. William F. McCleese, Acting Chief, CTD, and Mr. Bryant Mather, Director, SL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
calories per gram	4186.8	joules per kilogram
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
inches	25.4	millimetres
pounds per square inch	0.006894757	megapascals
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

1 Introduction

Pozzolans are materials which have little or no inherent cementitious properties, but which develop cementitious properties in the presence of calcium hydroxide (lime) and water. Pozzolans have been used since Roman times as ingredients of lime mortars. Such pozzolans were usually derived from natural deposits, principally volcanic ash. Many modern pozzolans are still derived from natural deposits, but the great bulk of pozzolan currently in use in the USA is derived from the combustion of powdered coal during electric power generation. This product is commonly called fly ash. The term "coal fly ash" is actually more correct, since other sources of fly ash exist, but are rarely used in the construction industry. The term pulverized fuel ash (pfa) is used in Great Britain.

There are currently three classes of pozzolan defined by the American Society for Testing and Materials (ASTM): Class N, Class C, and Class F. Class N are natural pozzolans: calcined shale, calcined volcanic ash, etc. Class F is fly ash nominally produced from anthracite, bituminous, and some sub-bituminous coals. It is required to show at least 70 percent $SiO_2 + Al_2O_3 + Fe_2O_3$ on chemical analysis. Class C is nominally produced from fly ash derived from combustion of lignite and some sub-bituminous coals and is only required to show at least 50 percent $SiO_2 + Al_2O_3 + Fe_2O_3$ on chemical analysis. All Class F fly ash also meets Class C requirements. Although not a specification requirement, CaO content of fly ash is probably more indicative of its performance properties than is $SiO_2 + Al_2O_3 + Fe_2O_3$. CaO contents of Class C fly ashes are higher than Class F fly ashes. This CaO often forms chemically active compounds that often considerably affect performance in portland-cement concrete. Many Class C fly ashes are hydraulic. Class N pozzolans are rarely used in the US construction industry, largely because of the severely competitive market presented by the coal fly ash industry.

Fly ash is an extremely abundant material. Total USA production in 1983 was 52.4 million tons, of which 3.6 million tons was used in cement and concrete products (Mehta 1985). An additional 5.3 million tons was used for other things, such as mud stabilization, agriculture, and raw material for cement manufacture, the remainder going to land fills (Diamond 1984). Not all fly ash is of sufficient quality to be suitable for use as a concrete ingredient but, except in temporary instances, there is no shortage of quality fly ash.

Although much concrete is still made that does not contain fly ash, rarely is fly ash prohibited from being included. Fly ash is a much cheaper material than portland cement, so that large replacements can result in significant economic savings. Dolen (1987) estimated that a 25 percent savings in materials cost was realized in the construction of the Upper Stillwater Dam through use of large amounts of fly ash.

Fly ash was first used in concrete in the USA in the 1932 (Mielenz 1983). The first large scale use of fly ash batched as a separate ingredient was in the Hungry Horse Dam, built by the Bureau of Reclamation from 1948 to 1953. This early use was almost exclusively of Class F fly ash. Class C fly ash has become particularly abundant in recent years due to increased use of lower grade coals for electric power production. Although there are circumstances where a particular Class C fly ash may not be appropriate, such as with alkali-reactive aggregates, or in high-sulfate environments, or in mass concrete, the limits of this material are now reasonably well defined (see EM 1110-2-2000) and it is now much more frequently used in concrete.

For many years, common practice was to use fly ash as part of the cementing medium in concrete (Mather 1968). The Corps of Engineers published guidance in 1960 (EM 1110-1-2007, Leber 1960) indicating that pozzolan should be used with cement for purposes of maximizing economy. At one time, the Corps of Engineers, in EM 1110-2-2000 (15 Dec 65, Table V, p. 60), specified Class F fly ash replacements for portland cement up to 35 percent (by volume) in interior mass concrete and up to 25 percent in exterior mass concrete. Class N pozzolan was allowed at 30 percent and 20 percent replacement levels, respectively. This guidance was modified in the 1985 edition of the Standard Practice, leaving the exact pozzolan level to the judgement of the design engineer. Current guidance is that maximum economic advantage of fly ash should be used within the constraints of good engineering practice.

Fly ash levels in Corps of Engineers' projects have largely remained at about 30 percent. If larger amounts could be used without detriment to engineering properties of concrete, then considerable money could be saved on materials since the cost of fly ash is largely governed by transportation costs. Also, the recycling of a waste product is a desirable result.

R. E. Davis, who was one of the early proponents of use of pozzolan in concrete, recommended that up to 50 percent replacement of portland cement might be suitable for some fly ash (Davis 1950). Work at the Waterways Experiment Station in the 1950's (described in detail below) supported the feasibility of the use of large amounts of fly ash in lean concretes for mass-concrete applications. Details of this work will be discussed in later sections of this report. Since then, there appears to have been a reluctance within the Corps of Engineers to incorporate high levels of fly ash replacement. This is probably at least partially a result of a natural caution engineers sometimes exhibit towards the use of novel materials or procedures in circumstances in which the cost of failure is very high. However, based on published reports

of Corps of Engineers work (Mather 1956) in which fly ash was used for as much as 60 percent of the cementing medium in mass concrete, some structures were built in which it was required that fly ash be 50 percent of the cementing medium. One such structure was the Revelstoke Dam built by British Columbia Hydro.

The purpose of this report is to summarize experience with high fly ash concrete, both as reported from laboratory studies and from published summaries of experience in construction. Areas in which increased research is necessary will be identified and a tentative outline of a procedure will be identified.

2 Effects of Large Quantities of Fly Ash on Properties of Fresh Concrete

Time of Setting

Setting is defined as the onset of rigidity in fresh concrete (Mindess and Young 1981). Although specific events are defined, i.e. initial and final setting, the process is actually continuous without apparently abrupt changes that conform to these events. Initial and final setting are arbitrarily defined levels of resistance to penetration by a calibrated device. However, they are useful parameters in that they do conform to approximate properties of the concrete that have meaning with respect to placing and finishing. Initial time of setting approximately represents the end of the workable period. Final time of setting approximately represents the time when measurable strength develops.

Specifications set a minimum level for initial time of setting, to guarantee a minimum working time, and set a maximum level for final time of setting of portland cement, to guarantee that finishing and other work can be continued on a reasonable schedule. Factors that cause small changes in time of setting may not be of importance, but large changes may cause considerable inconvenience in placing and finishing schedules.

Portland cement is the principal active ingredient in concrete that causes setting. For purposes of specification-compliance testing, time of setting is measured on paste specimens according to ASTM C 191 and C 266. These tests are performed at specified water-cement ratios, consequently their results are useful for comparative purposes but may not directly indicate the time of setting of a concrete made with the same materials. Time of setting is strongly affected by factors which often vary in field practice, but which are held constant by these test methods, such as temperature, water-cement ratio, cement-aggregate ratio, and chemical interactions among the ingredients of the concrete mixture. These paste-based methods are useful for detecting changes in cementitious systems and results are probably correlated with changes in

concrete. Time of setting of concrete is measured according to ASTM C 403, which uses the mortar fraction of the concrete for testing.

Fly ash usually has a tendency to retard the time of setting of cement relative to similar concrete made without fly ash. This phenomenon has long been recognized but considered to be inconsequential at the levels of fly ash conventionally used. This retardation stems from at least two apparently independent causes. First, replacement of portland cement with fly ash effectively dilutes the cement, resulting in a longer hydration time necessary for the hydration products of cement grains to make interconnections. Second, there may be a chemical effect on setting time that results from the introduction of the fly ash into the system. This being the case, it would appear that high replacements of portland cement by fly ash would cause an even greater increase in setting time relative to concretes with more conventional replacements.

Not a great deal of work has been published describing the effect of high fly ash contents on time of setting. These are summarized below.

Naik (1987) examined the effect of 35 to 55 percent (by mass) of Class C fly ash on time of setting. Initial time of setting increased about 1 hr for each 10 percent increase in fly ash content. Final time of setting increased about 90 min for every 10 percent increase in fly ash content. This effect was less pronounced for rich mixtures.

Ravina and Mehta (1986) reported increases in time of setting from a few minutes to a few hours. The effect was most pronounced in high-replacement concretes made with Class C fly ashes.

Sivasundaram, Carette, and Malhotra (1990) investigated two Class F fly ashes used at 60 percent (by mass) of total cementitious material at a w/c of 0.31. They found that initial time of setting was not changed relative to control, but that final time of setting ranged from 8 to 11 hr, which was about 3 hr more than controls.

Mukherjee, Loughborough, and Malhotra (1982) found that 37 percent Class F fly ash (by mass) caused a maximum delay in time of setting of 3 hr.

Majko and Pistilli (1984) reported extensive time-of-setting data for Class C based mixtures containing up to 36 percent fly ash. Control setting times of 6 to 8 hr (depending on mixture) were extended up to 2.5 hr at the maximum replacement. When water-reducing admixture was used in the mixtures, setting times were extended up to 6 hr for the higher fly ash content mixtures.

Ravina and Mehta (1986) reported setting time for both Class C and Class F based mixtures containing up to 50 percent fly ash. Initial time of setting was increased, relative to control, by from 20 min to 4 hr and final time of setting was increased from 1 to 5 hr, with the greatest increases occurring at

higher replacements and with the Class C ashes. Leaner mixtures also had longer setting times.

The effect of replacement level was examined at WES (unpublished data) from results of testing for several miscellaneous projects using paste methods (ASTM C 191, C 266). These were not controlled experiments in that a variety of fly ashes are represented and each was not represented at each replacement level. Consequently, conclusions are drawn from a less-than-rigorous analysis. Results are expressed as a percentage of control to put results on a more comparable basis. The increase in initial time of setting averaged less than 50 percent of control for low (about 20 percent) and moderate (35 to 40 percent) replacements, but increased to a mean of about 300 percent of control for high (about 70 percent) replacements. However, the 70 percent conditions was represented by only two fly ashes. The effect on final time of setting was somewhat less. The increase averaged about 25 percent for low and moderate replacement levels and about 100 percent for the high replacement levels.

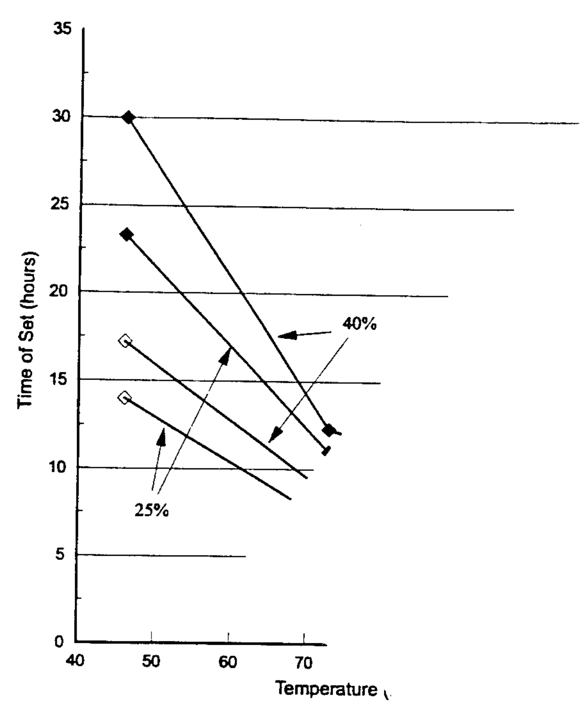

Figure 1. Time of setting versus temperature, two levels of cement replacement

Fly ash replacement level probably significantly interacts with temperature in its effect of time of setting. Some illustration of the importance of this interaction was revealed in other unpublished work conducted at WES involving time of setting of concrete (ASTM C 403). Results are illustrated in

Figure 1. Increasing amounts of fly ash resulted in increased times of initial setting, which were also affected by temperature. The final time of setting data were more strongly influenced by both fly ash amount and temperature.

There have been instances in Corps of Engineers' experience when use of large quantities of Class C fly ash accelerated the time of setting to the point where placing the concrete was impossible. This phenomenon is completely opposite to the common behavior, which is to delay time of setting. Little is known about this phenomenon, but since Class C fly ash will probably increase in use in concrete, it should probably be investigated further.

In summary, there appears to be no doubt that time of setting is normally delayed by the replacement of portland cement with fly ash in concrete, but the effect is not large for low to moderate replacement levels. The effect appears to be quite large for high replacement levels, but this depends largely on materials, temperature, and mixture proportions. It is recommended that preconstruction testing be done when large replacements of portland cement with fly ash are contemplated to determine the magnitude of any time-of-setting problem.

Workability, Water Requirement, and Bleeding

The effect of large amounts of fly ash on the workability of cementitious systems is difficult to address since it is common practice to proportion mixtures to a desired level of workability. When the adjustment involves changing the water content, the relevant measurable property is water requirement. Water requirement is the amount of water needed to obtain a defined level of workability, expressed as a percentage of control. Thus workability and water requirement tend to be different sides of the same phenomenon. The literature is rather extensive on the effects of fly ash on these properties for conventional levels of fly ash content, but it is not so extensive for very high fly ash levels.

Water required for constant workability is usually lower for fly ash-containing mixtures, but the amount of water reduction varies among fly ashes. At conventional replacement levels, Class C ashes generally tend to affect greater water reduction than do Class F ashes (Geber and Klieger 1986). Values for the former tend to run close to 90 percent of control, while values for the latter generally run above 95 percent of control. There have been reports of fly ashes from Australia and India that cause an increase in water demand relative to control (Berry 1979), but these are apparently uncommon.

Studies describing high-fly ash concrete often tend to report workability effects in qualitative terms. In general, there seems to be no undue concern about either workability or water requirement with high-fly ash mixtures, but differences in behavior relative to lower-fly ash contents have been noted. Dodson (1988) discusses how water-reducing admixtures seem to act in

reverse of normal action when used in high-fly-ash concrete. Some workers report a "gluey" (Mukherjee, Loughborough, and Malhotra 1982) or sticky consistency, but the effect was not severe enough to interfere with placing.

Dunstan and Joyce (1987) reported that the compactability of a 50 percent Class F mixture was a little more sensitive to water content than the comparable portland cement mixture, but not to the point of constituting a practical problem. Ravina and Mehta (1986) used a troweling test and found a general improvement in workability with increasing fly ash contents. The maximum ash content examined was 50 percent. This improvement is probably due to the effects of a higher volume of paste in the fly ash mixtures that resulted from the mixture proportioning technique. Tynes (1966) reported that a lean (2.5 sack) 52 percent fly ash mixture took longer to consolidate than a comparable control mixture. Joshi et al. (1987) found that workability of a 50 percent (mass) replacement improved, when measured by the Vebe (ACI 1992) test, for eight fly ashes studied. For 8 fly ashes at 50 percent replacement (by mass), They found that there was considerable variation among fly ashes in effect of water-reducing admixtures on slump.

For high-fly ash concrete, water requirement decreases with increasing fly ash in lean mixtures, but tends to increase with increasing fly ash content in richer mixtures (Cook 1983). Mather (1956) found a reduction of water demand with increasing fly ash content for both 0.5 and 0.8 w/c mixtures (Table 1).

Table 1
Water Requirement (lb/yd^3) for Equal Slump and Air Content

	w/c	
	0.5, rich	0.8, lean
no fly ash	265	281
30% fly ash	247	261
45% fly ash	235	261
60% fly ash	236	254

Fly ash could potentially affect bleeding through an increase in water demand or a delay in setting time. There seems to be no general consensus about the effects of fly ash on bleeding either at conventional replacement levels or at higher replacement levels. Ravina and Mehta (1986) report that there is no simple relationship between percent fly ash and bleeding, but that the phenomenon varies with source of fly ash. Very coarse fly ashes generally perform poorly in this regard. Tynes (1962, 1966) reported no problems with bleeding that could be attributed to fly ash. Some of the 37 mixtures examined contained more than 60 percent fly ash. Sivasundaram, Carette, and Malhotra (1989) reported no bleeding in mixtures containing 60

percent Class F fly ash, but the w/c was low. In contrast, McCoy and Mather (1956) reported that, in a 45 percent fly ash mixture, bleeding was greater than in control mixtures (9 percent vs. 4.5 percent).

In summary, workability, water requirement, and bleeding behavior tend to be material specific and can sometimes be a problem with high-fly ash mixtures, but they do not appear to be problems inherent to such mixtures. As with time of setting, preconstruction testing is recommended.

Air Entrainment

It is well known that the carbon content of fly ash can have an impact on the air-entraining admixture dosage required for a desired air content. Carbon content is rarely measured on fly ash, but is approximately indicated by loss on ignition (LOI) at 750 °C. The general belief is that target air contents can be achieved at almost any level of LOI, but for fly ashes whose LOI exceeds 6 percent, fairly small fluctuations can cause problems in controlling air. The effect of fly ash replacement level on the LOI-AEA dosage relationship is not well described. Dunstan and Joyce (1987) mentioned that control of air was a problem in a 50 percent fly ash paving mixture, but this was not quantitatively related to the level of fly ash. Joshi et al. (1987) reported significant variation AEA dosage requirement among several fly ashes in mixtures containing 50 percent fly ash, but, again, it was not demonstrated that this was caused by the high replacement level and this phenomenon is known even in mixtures with relatively low fly ash contents.

Mather (1954) gave data on air-entraining admixture demand of 0.5 and 0.8 w/c concrete with 45 percent replacement of each of four Class F fly ashes having carbon contents of 0.43, 3.17, 11.13, and 7.22 percent respectively, when used with two different portland cements. While the range in amount of admixture was from 146 to 1214 mL/yd^3, it was noted that the range due simply to change in cement and water-cement ratio was from 146 to 485. See Table 2.

Table 2
Air-entraining Admixture Demand and Drying Shrinkage of Fly Ash Concrete. From Mather (1956)

Type of Cement	Water-Cement Ratio	Amount of Neutralized Vinsol Resin Required to Produce 6.0 ± 0.5 percent Air in Concrete with ¾-in Aggregate, mL per cu yd				
			45% of cement replaced by fly ash			
		No Fly Ash	Fly Ash I 0.43% carbon	Fly Ash II 3.17% carbon	Fly Ash IV 7.22% carbon	Fly Ash III 11.13% carbon
II	0.5	485	348	647	886	1214
II	0.8	265	242	410	500	688
I[a]	0.5	248	248	531	732	1026
I[a]	0.8	146	162	339	428	601
		Drying Shrinkage of Concrete after Storage at 50% RH and 73.4 F to 180-Days Age, as Thousandths of a percent of 14-Day Length				
II	0.5	58	52	56	55	62
II	0.8	56	46	46	45	47
I[a]	0.5	56	49	49	55	58
I[a]	0.8	46	45	45	50	45

[a] high-alkali

3 Effects of Large Quantities of Fly Ash on Properties of Hardened Concrete

Strength

Strength is usually a property of concrete of interest, either because of load-bearing considerations or because of the constraint low early strength development can impose on construction schedules. Strength is one of the properties of concrete on which fly ash has a notable effect, but the size of the effect is strongly dependent on the w/c. When fly ash is used as a replacement for portland cement, reductions in early strength relative to the pure portland-cement concrete are common. When fly ash is used as an addition (in effect a replacement for fine aggregate), this early reduction is commonly not evident. A third procedure is to replace part of the portland cement and part of the fine aggregate with fly ash. Also, considerable adjustments to strength development can be made by modifying water to cement ratios combined with use of water-reducing admixtures.

When used as a replacement for portland cement, fly ash basically acts, at early ages, as a diluent of portland cement, contributing little directly to strength development. However, there is evidence that fly ash (or other finely divided material) does accelerate the early hydration of some portland-cement phases (Beedle et al. 1989, Domone 1989), so that the observed strength is somewhat greater than expected from the volumetric fraction of portland cement present in the mixture. Even so, the strength reduction caused by replacement of portland cement by fly ash is approximately linearly related to the amount of that replacement up to the range of 60 to 70 percent replacement (see Figures 2 and 3). Therefore, the prediction of early-age strength for a particular replacement level is relatively simple from a relatively small amount of data.

The time at which the fly ash begins to contribute to strength also depends on the kind of the fly ash. This varies from a few days or sooner, for Class C fly ashes, to a few weeks, for Class F fly ashes. Strengths then gradually increase with respect to the control. Whether the strength of the fly

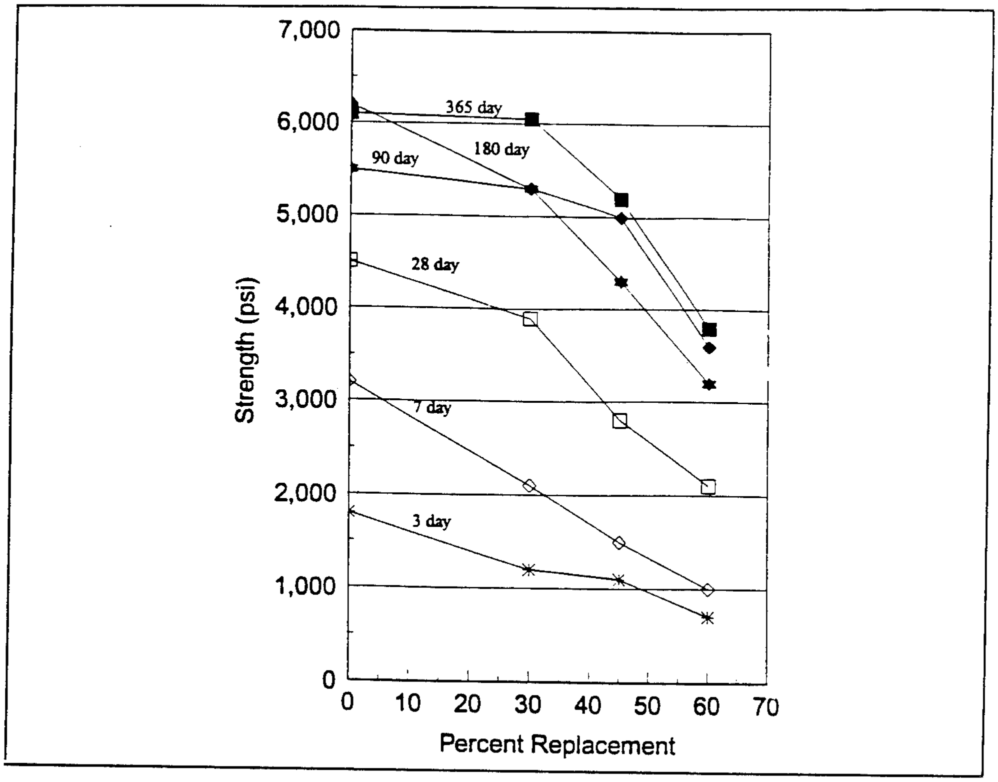

Figure 2. Strength versus percent replacement of cement with fly ash, w/c = 0.5

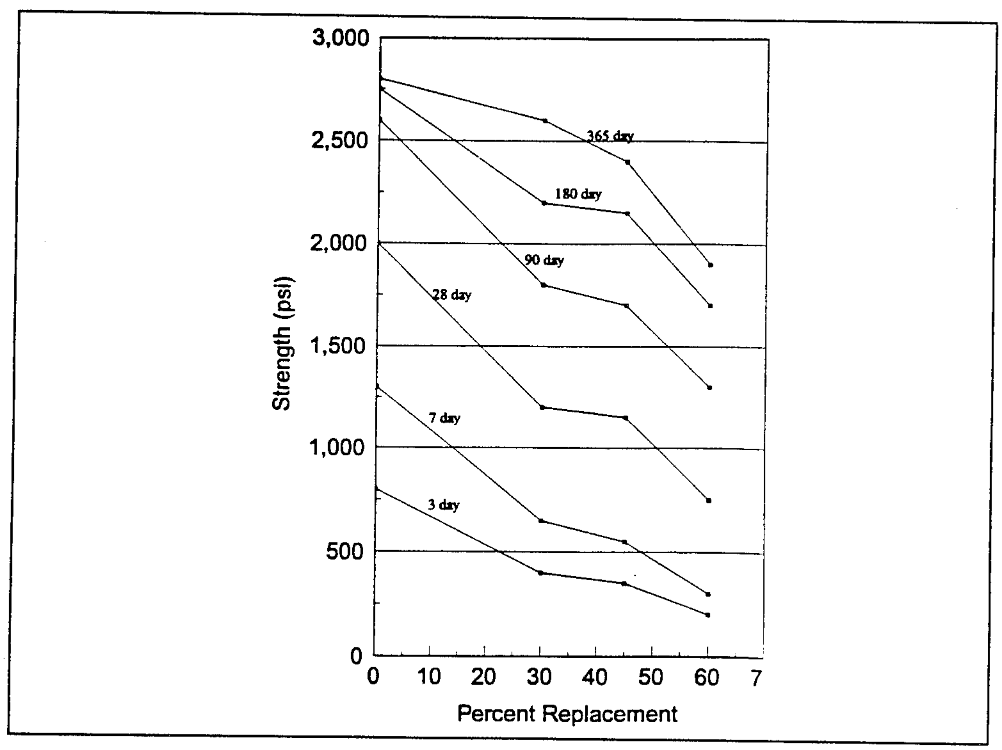

Figure 3. Strength versus percent replacement of cement with fly ash, w/c = 0.8

ash-portland cement mixtures ultimately equals or exceeds that of the control mixture without fly ash depends on the mixture design procedure, the type of fly ash, and the water-cement ratio.

When the replacement is with Class F fly ash, ultimate strengths rarely reach those of the control mixtures unless the percent replacement is low (about 15 percent) (Mather 1968, Cook 1983, Sivasundaram et al. (1990), Joshi et al. 1987). In the case of high replacements, the ultimate strength may not exceed 70 percent of the control mixture, as illustrated in Figures 2 and 3, taken from Mather (1965). This is probably due to a depletion of calcium hydroxide in the system. This effect is not apparent when low water-cement ratios are used, as is described below in the considerable literature on such of mixtures.

Fly ash reacts with calcium ion in the pore solution of concrete and water to form hydration products (CSH) that contribute to strength. The calcium hydroxide comes from the hydrating portland cement fraction of the mixture and may be in limited supply. Helmuth (1987) calculated that, in low-calcium (Class F) fly ash mixtures containing as little as about 22 percent fly ash (by mass), the fly ash consumes all of the calcium hydroxide produced. Dodson (1988) calculated this figure to be 20 percent fly ash, but the exact figure probably varies with cement since cement chemistry affects the amount of calcium hydroxide produced. No matter which portland cement is used, it is probable that calcium hydroxide would become limiting at high replacement levels. Class C fly ashes typically contain substantial quantities of calcium compounds and these often result in considerable amounts of lime being introduced into the system relative to Class F fly ashes. Therefore, Class C-based mixtures should not become so easily lime restricted and ultimate strengths of high-replacement mixtures are likely to be higher for Class C-based mixtures than for Class F-based mixtures.

Berry et al. (1992) also discusses at some length the mechanism by which high-fly ash concretes gain strength at early ages, apparently beyond the level expected from the portland cement fraction. They conclude that chemical reactions between the pore fluids and the amorphous silico-aluminate glasses occurs to appreciable degree even at early ages and with large replacements of portland cement with fly ash. Calcium hydroxide continued to be abundant through 180 days, the last age data were collected, indicating no limitation in reaction due to depletion of this phase. In Part 2 of the same work, Zhang et al. (1992) concluded that fly ash acts as a reactive microaggregate and that complete hydration of the fly ash particles does not occur.

Also in the case of Class F fly ashes, there appears to be a retardation of strength development beyond that expected from simple dilution of the portland cement during the first day or two, which then disappears after a few days. This appears as a negative trend in the strength-versus-time curve when strength is expressed as a percentage of the control (Figure 4).

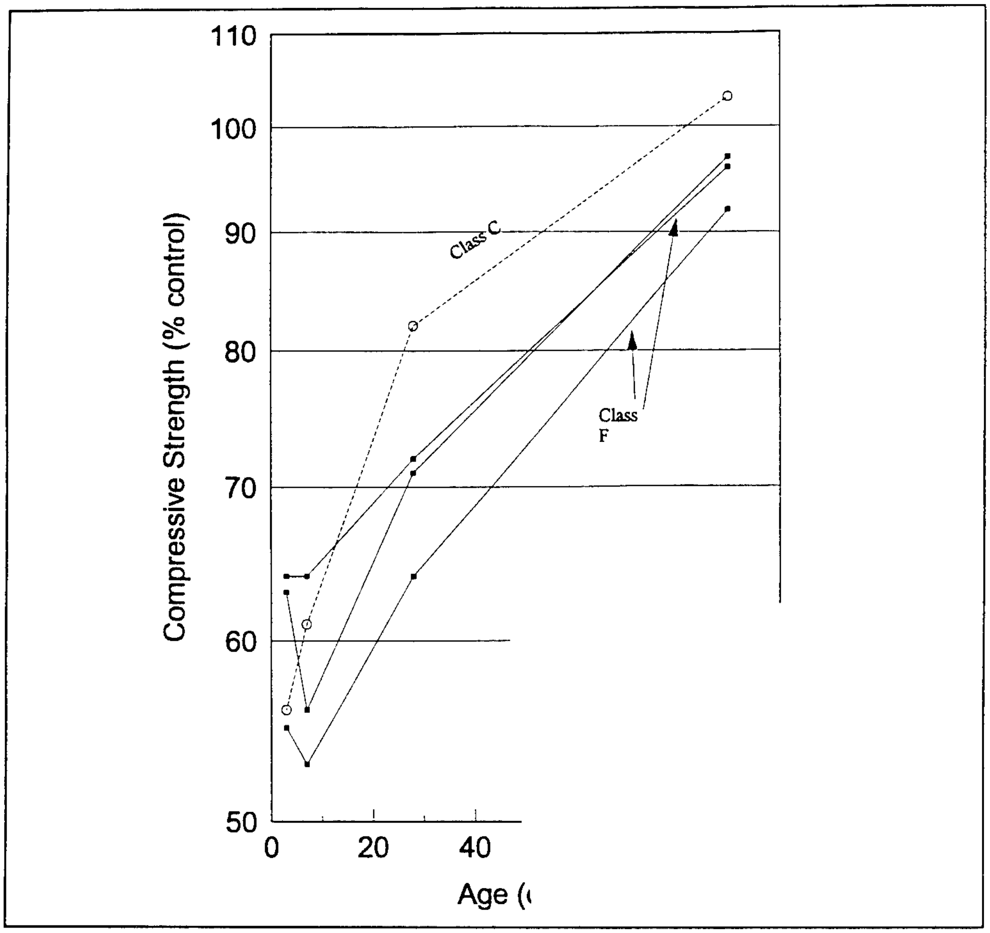

Figure 4. Strength (percent of control) versus age for four fly ashes at 30 percent replacement of cement

Dunstan (1981A, 1983) investigated the relationships between w/c and strength change with the substitution of a large quantities of fly ash. Changing the w/c has a stronger effect on cement-fly ash mixtures than it does on pure portland-cement mixtures. For example, above a w/c of 0.54, 60 percent fly ash was found to make no contribution to strength at 7 days. At w/c's greater than 0.70, fly ash makes no contribution to strength until 28 days.

In summary, simple replacement of portland cement with fly ash causes predictable reductions in early strength and some reductions in long term strength, but within reason, strengths can be engineered for most fly ash levels by choice of fly ash, manipulation of w/c, and cementitious materials content of the concrete according to basic concrete principles. Considerable laboratory work may be required to identify the patterns for a given set of materials. Such laboratory work is quite expensive to execute when performed on concretes. However, it is likely that for a given set of materials, concrete and mortar strengths will be correlated. If reasonably accurate estimates of regression coefficients can be made by making only a

few concrete mixtures, then considerable exploration of the effects of variations in mixture design on strength can be made using mortars and at very little cost. This approach would be particularly attractive if it turned out that the relationships between mortar and concrete properties were linear. Then very few concrete mixtures would be required to calibrate the relationship.

Following are brief summaries of strength studies and summaries of construction projects that involved concrete containing high volumes of fly ash.

Some of the very early work on the effect of high cement-replacement levels with pozzolans on relatively lean concretes was conducted at WES during the 1950's. McCoy and Mather (1956) reported results of field-scale concrete tests (5 ft by 5 ft by 10 ft blocks) for mixtures containing 45 percent Class F fly ash (by solid volume) using 3 in. and 6 in. aggregate. Total cementitious materials contents were about 200 lb/yd^3 and the w/c was 0.80. Strengths at 7, 28, and 90 days were about 600 psi, 1150 psi, and 1910 psi, respectively. These were 31 percent, 58 percent, and 80 percent of control, respectively. Aggregate size had little effect on strength. Such strengths were once considered to be reasonably adequate for mass concrete (Tynes 1962), although higher strengths are now usually specified.

Tynes (1966) reported compressive strengths of laboratory mixtures containing 94 lb of cement and additional Class F fly ash so that the fly ash ranged from 52 to 71 percent (by mass) of the total cementitious material (total cementitious materials varied from 194 to 319 lb/yd^3). Control mixtures contained 189 lb/yd^3 of cement. Strengths at 3 days tended to be substantially lower than control at 3 days (about 60 percent) but strengths at 90 days had exceeded control at 90 days. The range of 3-day strengths among all fly ash mixtures was 590 psi to 760 psi. The range of 90-day strengths was 2480 to 3070 psi. Water-cement ratios ranged from 0.4 to 0.6. Strengths tended to increase at each age with increasing amounts of fly ash, except for the 71 percent mixture, which showed some strength loss. The strength-increase pattern probably resulted from the increase in paste fraction due to increased fly ash content and reduced water-cement ratio. The decrease at the highest fly ash percentage was attributed to lime depletion.

Tynes (1966) further reported that field blocks made with these same mixtures gave somewhat lower strengths than the same mixture in laboratory tests ($<$500 psi at 3 days, $<$2000 psi at 90 days). This decrease was rationalized as due to variation in properties of cement and fly ash among lots used between the two programs.

Mather (1965) reported results of 193 laboratory concretes made with several pozzolans and slags. Discussion here focuses on the fly ash mixtures. Two types of concretes were made: one was essentially a structural concrete, containing 500 lb/yd^3 of cementitious materials at a w/c of 0.5; the other was essentially a mass concrete, containing 200 lb/yd^3 of cementitious materials at

a w/c of 0.8. Strengths were measured to 10 yrs. At 60 percent replacement with Class F fly ash, strength relative to control varied from about 30 percent at early ages (a few days) to about 60 percent at ten years. Generally, strengths of all fly ash containing mixtures were less than control, even at 10 years.

This work at WES was directed primarily at exploring use of pozzolan replacements for mass concrete applications. It was concluded that even relatively high replacement levels were reasonable for this application, but apparently no structures were constructed using substantially more than the 30 to 35 percent maximum recommended by Corps of Engineers guidance until in the 1980's when 40 to 50 percent fly ash was used in construction of the Old River Control Auxiliary Structure and in several navigation structures on the Red River, all in Louisiana.

The earliest use of high fly ash contents was reported by M.R.E. Dunstan (1981B) for use in roller-compacted concrete and for the structural concrete used in the slip forming of the exterior concrete used in this type of construction. Roller compacted concrete is a relatively low water-cement ratio material that must contain a high paste fraction for adequate bonding between layers. High replacement levels of portland cement with fly ash, or other pozzolan, are then necessary when this technology is used in mass-concrete applications to control heat of hydration. Mixture design work pursuant to construction of Milton Brook Dam indicated that fly ash replacements of 70 to 80 percent, by volume, and total cementitious materials of 450 lb/yd^3 to be optimum (Dunstan 1983).

In collateral laboratory investigations concerned with use of high fly ash replacements in structural concrete, Dunstan (1983) found 50 percent replacement levels not too high to yield reasonable early strength (e.g. 4200 psi at 7 days). Such strengths are achieved through a reasonably high paste fraction and a low w/c (about 0.25), requiring use of a high-range water reducer.

Dolen (1987) documented the roller-compacted concrete used in the construction of Upper Stillwater Dam. Fly ash (Class F) comprised up to 65 percent of the cementitious material. Early strength was considerably lower than for the equivalent pure portland-cement concrete, but later strengths were higher. In this type of construction technology, low early strengths are not important because higher early-strength concrete is used for the facing material that serves as a form for the lower-strength fill. Lower-than-expected strength gain was experienced during one construction season, which was attributed to the coarse nature (large percentage retained on a 45-sieve) of some of the fly ash used.

Recent laboratory studies have focused on ways to use large quantities of fly ash but yet still get high early strengths. These have mostly exploited low water-cementitious materials ratios.

Majko and Pistilli (1984) reported the effects of replacing various proportions of portland cement (on a mass basis) with Class C fly ash. For equivalent cement plus fly ash contents, approximately equal strengths were obtained regardless of the fly ash percentage. This generalization appeared to hold for total cementitious contents (cement plus fly ash) in the range of 400 to 600 lb/yd^3. Higher replacement mixtures required lower w/c's to achieve this equivalency, but the amount of WRA required was constant. Apparently water reducing effects contributed by the fly ash allowed the additional water-reduction without additional WRA. Probably because of the relatively low water-cement ratios (ranged from 0.34 to 0.46), strengths above 1000 psi at 1 day and above 3000 psi at 28 days could be achieved with a wide range of cement-fly ash proportions. Much higher strengths than these were achieved at the highest cement plus fly ash contents and at the lowest water-cement ratios. The optimum fly ash percentage, defined as that percentage that gives the highest strength at a given age, appeared to differ with the presence or absence of WRA.

Naik (1987) conducted a laboratory investigation on a series of mixtures using Type I portland cement and Class C fly ash. Fly ash contents were 0 percent to 60 percent (by mass). Total cementitious materials content was nominally 450, 550, and 650 lb/yd^3, although this varied some with fly ash levels. Strengths increased with cement plus fly ash content, as expected. However, very low early strengths (3 and 7 days) were measured at the highest cement-replacement levels (50, 60 percent). This effect appeared to get worse at the highest total cementitious materials contents. The author attributed this to the cylinders being "green" when tested. For the 650 lb/yd^3 mixtures, this green period persisted at least through 7 days. These mixtures then gained strength very rapidly once they passed the "green" period.

Malhotra and associates have published results of several studies concerning strength in high-fly ash concretes. Malhotra and Painter (1988) investigated strength development of portland cement-fly ash mixtures in which the fly ash proportion varied from about 40 percent to 60 percent by mass. Class F fly ash was used. Portland cement content was held constant at 150 kg/m^3 (262 lb/yd^3). Water content was also held constant. Cement-fly ash proportions were realized by simple addition of fly ash. This design procedure then necessarily resulted in higher total cementitious materials contents and lower w/c's as percent fly ash was increased. Water-cement ratios were kept low (0.28-0.42) using high-range water reducer. Three-day strength varied from 1100 psi to 2300 psi. Twenty-eight-day strengths varied from 2300 psi to 5300 psi. Ninety-one-day strengths varied from 2833 psi to 6700 psi. In each case, the higher range of strength was obtained at the highest fly ash content, which was also the lowest w/c.

In another study Mukherjee et al. (1982) examined concrete containing 37 percent Class F fly ash, by mass, using high-range water reducer to get a water-to-cementitious-materials ratio of 0.35. Strengths were 70 percent of control at 7 days and 90 percent of control at 28 days.

Langley, Carette, and Malhotra (1989) examined 56 percent fly ash concrete. Early strengths were lower than control, but there was significant strength gain after 7 days. Properties of the fly ash allowed some water reduction, which contributed to strength properties.

Sivasundaram et al. (1989) conducted a similar study at 60 percent fly ash and noted that strength of cement-fly ash mixtures was less than control even at one year. They attributed some of this to greater sensitivity of these mixtures to moist curing. In other work, the same authors (Sivasundaram et al. 1990) concluded that high fly ash contents worked well but that there was considerable variation among fly ashes, strengths were not critically dependent on total cementitious materials contents (at least at the low w/c used in these studies), and very high dosages of high-range water reducer were required at the low w/c's used in this study (0.22 and 0.33).

Giaccio and Malhotra (1988) looked at the effect of beneficiation of the fly ash (removal of material larger than 45 microns) on strength development of low w/c (0.32), high fly ash (56 percent by mass) concretes. Class F fly ashes were used. Strengths were good with all fly ashes and there did not appear to be much effect on strength due to beneficiation. They also report flexural and splitting tensile strengths.

Sivasundaram, Carette, and Malhotra (1990) looked at long-term strength using cores taken from a cube of concrete (1.5 × 1.5 × 1.5 m). The mixture contained 580 lb/yd^3 of cement + fly ash (56 percent Class F fly ash by mass) at a w/c of 0.28. The concrete reached 73 percent of its 3.5 year strength (~ 10,000 psi) by 90 days. Modulus-of-elasticity, pulse-velocity, and temperature-rise data were also reported.

Joshi et al. (1987) looked at 8 fly ashes at 50 percent replacement, by mass. Class C based mixtures showed ultimate strengths that were higher than control. Class F based mixtures showed 20 to 30 percent less strength than controls at late ages. Mixtures containing HRWR and AEA showed less strength than mixtures without these admixtures.

In work on some of the same fly ashes, Day (1990A) investigated the effects of curing temperature and evaluated cost factors associated with replacement level. Strength of fly ash mixtures responded more to early elevated-temperature curing than did controls, but fly ash mixtures were more retarded in cold than were controls. The cost of making concrete tends to decrease with increasing fly ash content, whether this is calculated on a per-yard basis or on an equivalent-strength basis (see Figures 5 and 6).

Heat of Hydration

The heat evolved during hydration of cementitious materials is important in mass-concrete construction because of the thermal stresses that can develop.

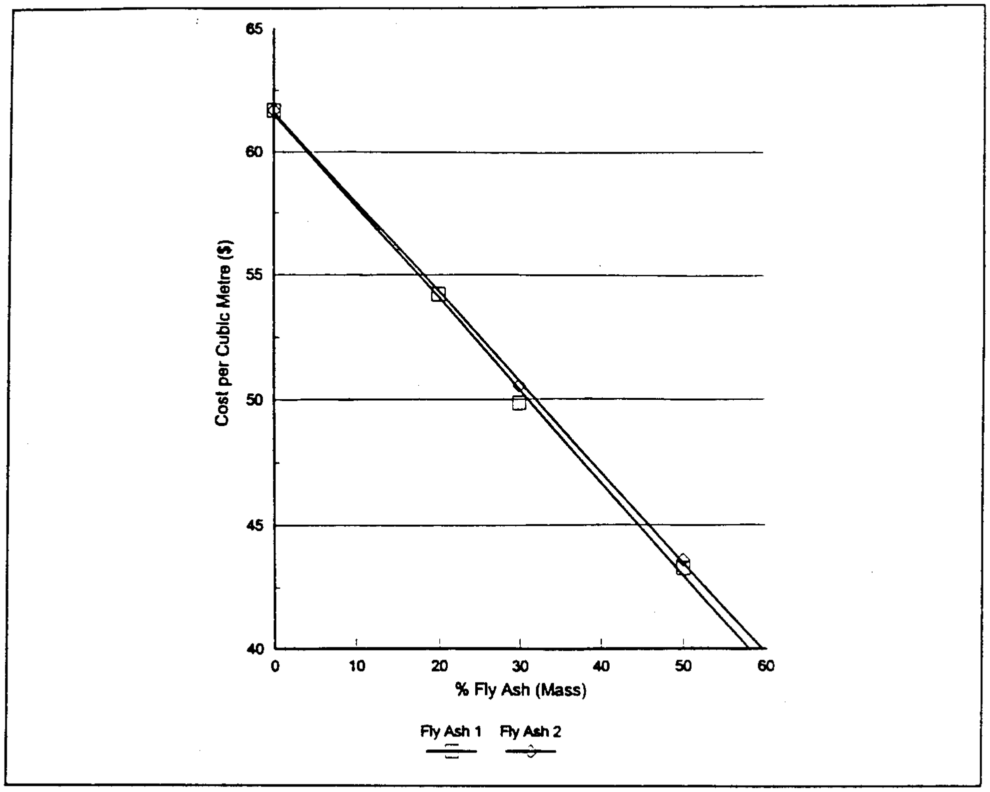

Figure 5. Cost of concrete at various fly ash contents

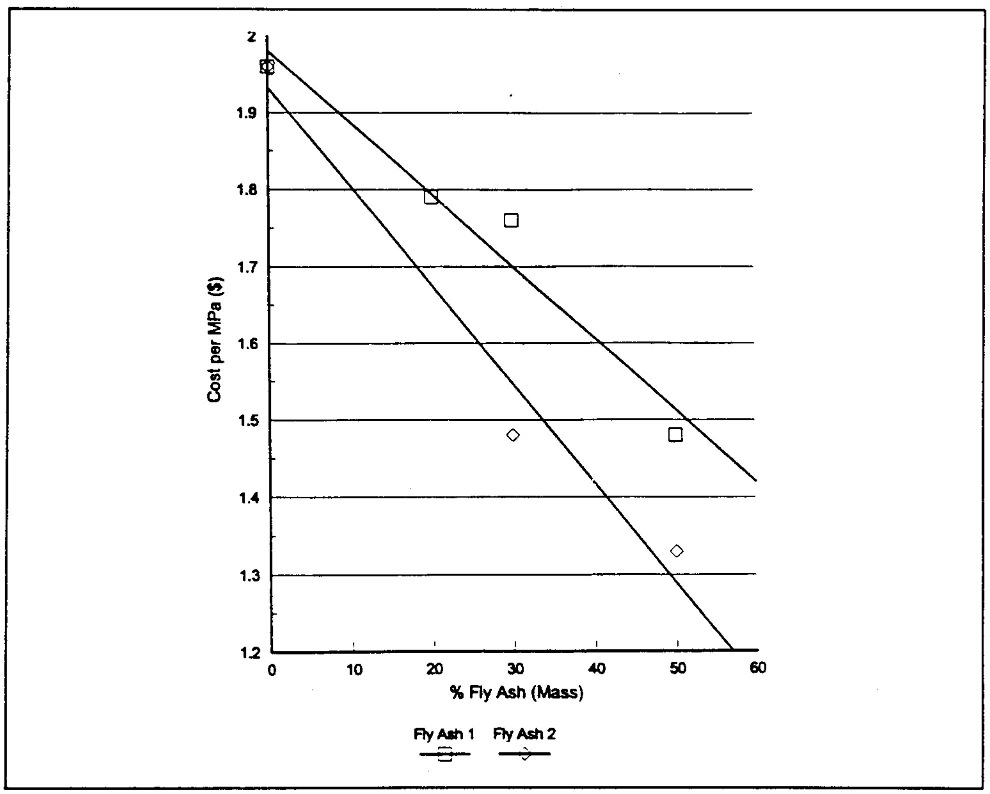

Figure 6. Cost of concrete per MPa at 28 days at various fly ash levels

Corps of Engineers guidance has sought to control this by either setting limits on the heat of hydration of the portland cement or by recommending use of Class F fly ash in the mixture, or some combination of these two approaches. Controlling the thermal stress problem is more complicated than setting limits on materials. This phenomenon is dependent not only on the heat evolved by the cementitious materials, but also on the amount of these materials in the concrete, the placing and curing temperatures, insulation, dimensions of the placement, heat capacity of aggregates, and coefficient of thermal expansion of the concrete. Analytical approaches to this complex problem exist, but they are somewhat expensive to use.

Practice has been to use the heat of hydration of the portland cement at 7 days as the standard for determining whether a cement is adequate for use in mass concrete construction. This specification is generally set at 70 calories per gram of cement, as per ASTM C 150. Some project specifications have allowed this to be increased to 80 calories per gram if Class F fly ash is included as a partial portland-cement replacement in the concrete mixture. The rationale for this modification is that Class F fly ash replacement of portland cement, in the amounts conventionally used (20 to 30 percent), will usually result in a heat of hydration of the combined cementitious materials of less than 70 cal/g if the cement evolves less than 80 cal/g. Other project specifications maintain the requirement of 70 cal/g for the portland cement and then further specify use of Class F fly ash, so that the heat of hydration of the combined materials is less than 70 cal/g. Sometimes portland cements show considerable variation in heat of hydration, so that when replaced at 30 percent by Class F fly ash, the resulting heat of hydration of the mixture may be as low as 50 cal/g. Early strength gain is often a problem with such mixtures.

No heat of hydration requirements are put on fly ash even though some Class C fly ashes evolve heat comparable to portland cement. The approach taken in developing project specifications is generally to determine the effect on heat evolution of various replacements of cement by fly ash. This is done along with strength gain determinations and then an optimum replacement level chosen.

Use of Class F fly ash in large replacements was investigated by Tynes (1962, 1966). Fly ash contents varied from 52 percent (by mass) to 71 percent. Table 3 summarizes results, expressed as percent of control.

Table 3
Heat of Hydration of High-Fly Ash Mixtures, % of Control

Reference	% Fly Ash	3 Day	28 Day	365 Day
Tynes (1962)	52 71	51 48	67 53	
Tynes (1966)	52 71	70 39		66 49

The results reported in these two studies are consistent in that large reductions in heat evolution were obtained with large fly ash contents and these reductions continued to be expressed at later ages. There was considerable variation among conditions concerning how the relative amount of heat evolved changed with time. There appeared to be little time dependence for some mixtures while others showed an relative increase in heat evolved with time. Some of this ambiguity may be due to a relatively large experimental error. Replicate data were not reported, so that experimental error could not be estimated. The method for measuring heat of hydration (ASTM C 186) is inherently quite variable as it is currently described, and was purportedly more variable at the time when these studies were completed. Unless some compensation for this large error is employed, such as comparing averages of replicate data, results can appear inconsistent.

Reinhold et al. (1986) reported 7- and 28-day heat of hydration data for 10 pozzolans blended with 2 cements (Type I and II) at 30 percent and 60 percent replacements, by volume. The pozzolans included 6 Class F fly ashes, 2 Class C fly ashes, 2 silica fumes, and 1 Class N pozzolan. There was considerable variation among pozzolans in contribution to heat evolution. Multiple regression analysis of the effects of the properties of the fly ash on relative heat of hydration (percent of control) showed that percent replacement, CaO content, and Blaine fineness accounted for most of the variation among materials. The regression equations are as follows:

$$HH_{7day}(\%control) = 96 - 0.72R + 0.64CaO + 0.00027B$$

$$HH_{28day}(\%control) = 94 - 0.56R + 0.62CaO + 0.0030B$$

where R is the percent replacement of portland cement by pozzolan, by volume, and B is the Blaine fineness (cm^2/g). The multiple correlation coefficient (r) was 0.82 for the 7-day data and 0.89 for the 28-day data. The two equations are similar except for the coefficient representing the effect of percent replacement. This effect was much stronger at 7 days than at 28 days. This is reasonable since many pozzolans react very little at early ages, acting very much as a simple diluent of the portland cement.

Pozzolans with very high CaO contents evolved about as much heat as the portland cement. For example, a Class C fly ash with 29 percent CaO evolved heat equal to 99 percent of control at 7 days and 96 percent of control at 28 days when at 30 percent replacement, and 101 percent of control at 7 days and 97 percent of control at 28 days when at 60 percent replacement. Similar results were obtained with different materials by Poole et al. (1990).

In unpublished work at WES that examined heat of hydration at earlier ages, it was found that even for high-CaO fly ashes, some reduction in heat was achieved at one and three days, while 7-day results were comparable to control values. The relationship between reduction in heat of hydration and fly ash content was linear at early ages for all materials studied. This linearity tended to disappear with age, first in the case of the Class C fly ashes and then with the Class F ashes (Figure 7).

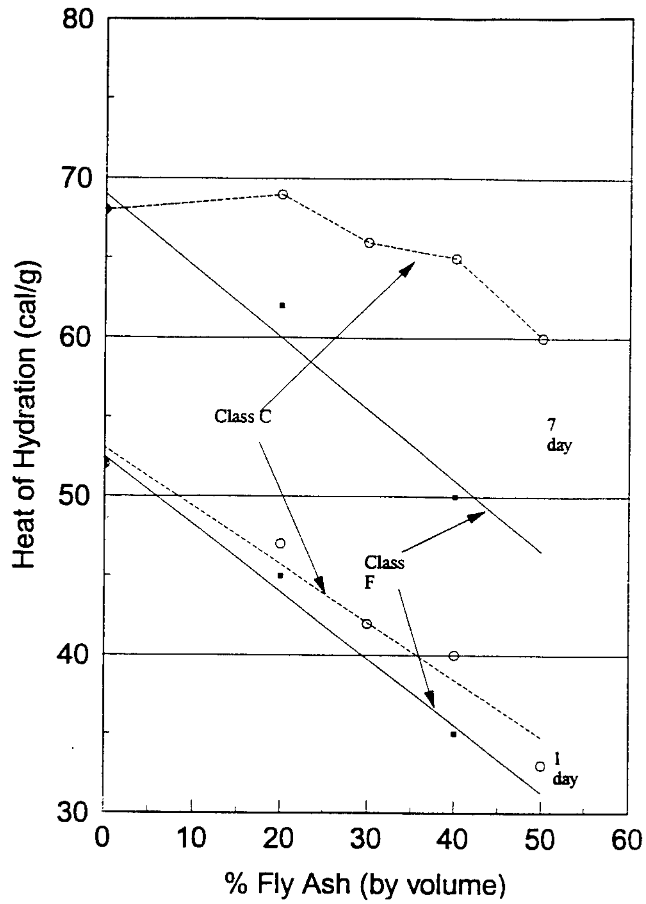

Figure 7. Heat of hydration vs percent fly ash, comparison of a Class C and a Class F fly ash

In summary, heat of hydration measurements are not completely adequate to describe early thermal behavior of concrete, but they are a useful guide to relative thermal behavior of materials. The effect of fly ash on the heat of hydration of portland cement systems varies with properties of the fly ash. Fly ashes with a high CaO content or that are very finely divided contribute significant amounts of heat by 7 days. Low-calcium fly ashes continue to provide reductions in heat evolution at later ages. Heat evolution of high-fly ash mixtures appears to be reasonably represented by an extrapolation of behavior of lower-fly ash mixtures.

Creep

The effect of fly ash replacement of portland cement on creep, the slow continued deformation under load (Lea 1970), does not appear to be well documented. In general, conditions that increase drying shrinkage and/or reduce strength development rate tend to increase creep (Mindess and Young 1981; Lea 1970). However, there are a number of qualifiers. The tendency of a given concrete to creep is not a static property, but varies with age, time of loading, temperature, and curing. Therefore, a general statement about the effects of fly ash may be difficult to develop.

Only three citations were found that addressed creep in high fly ash concretes. In Reinhold et al. (1986), a Class C and a Class F fly ash were examined at 30 percent and 60 percent replacement levels. The specific creep increased with increasing fly ash replacement when specimens were loaded at 7 days. Class F-based mixtures showed slightly more creep than Class C-based mixtures. When the specimens were loaded at 28 days, there was no increase in creep of fly ash specimens relative to controls. Swamy and Mahmud (1989) found essentially no effect due to fly ash in 50 percent Class F concretes. Day (1990B) examined 3 Class F and 2 Class C fly ashes at up to 50 percent of cementitious materials (by mass). Specimens were loaded in both wet and dry condition. He found that creep was reduced relative to controls.

Drying Shrinkage

Summarizing early experience with concrete tests, Davis (1950) reported that fly ash generally causes an increase in drying shrinkage, except when it is of a low carbon content and high fineness. Berry (1979) reported that fly ash in practical proportions does not significantly influence drying shrinkage of concretes. These apparent discrepancies may be due to differences in methods or mixture properties. Helmuth (1987) emphasizes the criticality of degree of hydration (i.e. moist curing) that occurs prior to exposure to a drying environment.

Several studies looked at the effects of drying shrinkage when higher levels of fly ash were used. Sivasundaram, Carette, and Malhotra (1989) reported on 2 Class F fly ashes at 60 percent (mass) of cementitious materials at low w/c (0.36). They found that such fly ash mixtures lost more water than non-fly ash controls, but that length change was about the same. They found improved performance relative to control if moist curing was extended to 90 days. Langley, Carette, and Malhotra (1989) found slightly improved performance of fly ash concretes relative to controls containing 56 percent Class F fly ash (mass). Water-cementitious materials ratios varied from 0.28 to 0.45. Swamy and Mahmud (1989) investigated 50 percent Class F-replacement concrete mixtures at w/c's of 0.32 to 0.61. They found that about 50 percent of drying shrinkage occurred in the first 7 days for mixtures

moist cured for one day. Values ranged from 0.039 to 0.49 percent, which were comparable to published values for conventional concretes. Day (1990B) looked at 3 Class F and 2 Class C fly ashes at up to 50 percent of cementitious materials (by mass). He found some improvement in performance of fly ash mixtures relative to controls. In unpublished data, Buck examined drying shrinkage of mortar bars made with two portland cements and one Class C fly ash tested according to ASTM C 311, except for variations in fly ash content. As illustrated in Figure 8, performance at moderate substitutions of fly ash (30 to 40 percent by volume) was variable, but there was a general decrease with higher fly ash replacements (60 to 65 percent). These results are confounded somewhat by a general decline in w/c with increasing fly ash substitutions, although this decline was not large.

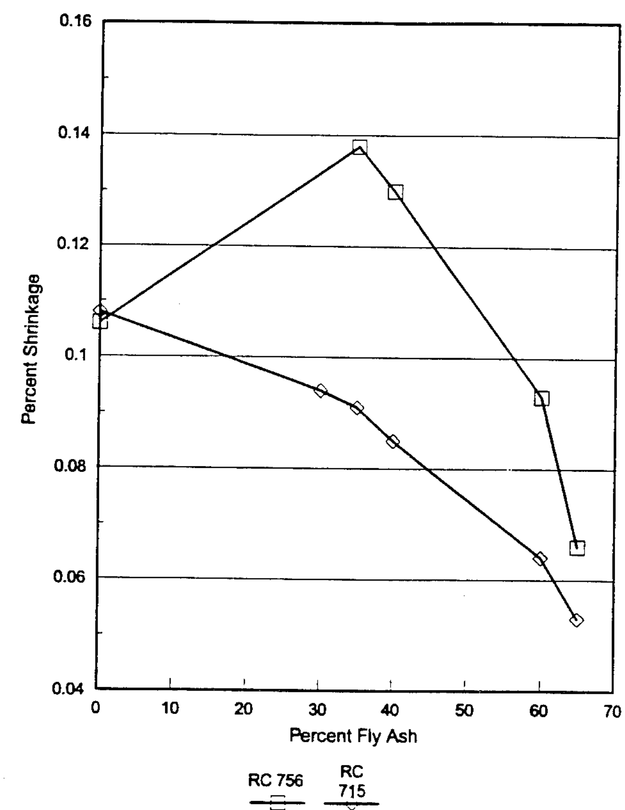

Figure 8. Drying shrinkage versus percent fly ash, comparison of two cements

In summary, there appears to be no serious indication that large replacements of portland cement with fly ash cause significant drying-shrinkage problems.

Curing

It is known from strength-development studies that concretes containing fly ash generally require longer moist curing than pure portland-cement concretes (Mather 1968; Gebler and Klieger 1986; Langley, Carette, and Malhotra 1989). Thomas (1989) confirmed this at the microstructural level. He looked at pozzolanic action, as measured by lime consumption and microstructure refinement. He found that fly ash-containing pastes (30 percent) were more sensitive to relative humidity than pure portland-cement pastes.

Haque et al. (1986) investigated the effects of curing of high-fly ash concretes on strength. Their principal concern was for strength development in thin structural members that might not get long curing. Fly ash contents ranged from 50 percent to 75 percent for Class C fly ash and 20 percent to 50 percent for Class F fly ash (by mass of cementitious materials). They compared strength development of 4 × 8 in cylinders cured in fog (95±5 percent relative humidity) with specimens stored in lab air at 50 percent relative humidity. Mixtures with higher fly ash contents did show less strength gain in the drier environment when compared with mixtures made with either low fly ash contents or with no fly ash. The authors believed that this effect would be critical for small cross-section structural concrete but not for mass concrete, where small surface-to-volume ratios typically exist.

4 Effects of Large Quantities of Fly Ash on Durability of Concrete

An extensive literature has been developed concerning the effects of fly ash on durability of concrete. These will not be reviewed here, but the general sense of this literature is that, with a few exceptions (e.g. sometimes use of Class C fly ash in high sulfate environments or with alkali-reactive aggregate), fly ash contents of 20 to 30 percent generally enhance resistance to a number of modes of concrete deterioration, or at least do not detract from it. Much less work has been reported for high-fly ash concretes.

Resistance to Freezing and Thawing

Resistance to freezing and thawing, as measured by ASTM C 666, is not negatively affected by high fly ash levels, but surface scaling is apparently common. Berry (1979) commented that the effect of fly ash on resistance to freezing and thawing is more a secondary result of its effect on AEA dosage requirements than a result of a direct affect on air-void patterns.

Sivasundaram et al. (1989) reported results for freezing and thawing (ASTM C 666) on concretes containing 60 percent (by mass) Class F fly ash (650 lb cementitious materials per yd, w/c=0.31). Air contents varied from 4 to 6 percent. Relative durability after 300 cycles was greater than 90 percent of control, but there was considerable surface scaling.

In similar studies using similar materials and mixture proportions, Malhotra (1990) and Giaccio and Malhotra (1988) reported relative durabilities of greater than 99 percent and 95 percent, respectively, after 300 cycles, with some surface scaling.

Langley, Carette, and Malhotra (1989) examined mixtures containing 56 percent fly ash, by mass. Air-void spacing was greater than in control mixtures, but this may have been a secondary effect of the high range water

reducer. Even so, the fly ash mixtures performed slightly better than controls in ASTM C 666 tests.

Joshi et al. (1987) examined 8 fly ashes in 50 percent mixtures (by mass). They noted that some of the mixtures showed some surface scaling, but otherwise performed well in the C 666 test.

Sulfate Resistance

The effects of fly ash, in normal proportions, on sulfate resistance has been well documented. In general, Class F fly ashes increase sulfate resistance, while some or most Class C fly ashes do not, although there are exceptions for both classes. The same behavior appears to hold for high fly ash concretes or mortars. Reports of four studies were found.

Dodson (1988) reported on a Class C fly ash that performed poorly when used at 23 percent (by mass of cement), but when used at 71 percent, there was essentially no deterioration.

Day and Joshi (1986) looked at three Class F and one Class C fly ash at 50 percent (by mass of cement). The Class F fly ashes performed well at this level. The Class C fly ash did not.

Joshi et al. (1987) looked at 8 fly ashes (6 Class F and 2 Class C) at 50 percent, by mass. One Class C fly ash performed badly, but the others performed well in that expansions for mortar bars was less than 0.1 percent at one year. An extension of this work was published by Day (1990B), reporting essentially the same results.

Buck (1988) tested a Class C fly ash at replacements up 65 percent in a high-C_3A cement mixture tested according to ASTM C 1012. Good performance was obtained at 50 percent replacement (0.06 percent expansion at 365 days), with little additional benefit at 65 percent replacement.

Alkali-Silica Reaction

High fly ash levels appear to enhance resistance alkali-silica reaction.

Pepper and Mather (1959) examined four fly ashes at 22.5 percent and 45 percent replacement, by volume, and found that the higher-replacement mixtures consistently gave smaller length changes than the lower-replacement mixtures in tests similar in design to ASTM C 227.

Buck and Mather (1987) studied nine fly ashes at 30 percent and 50 percent replacement, by volume, tested according to ASTM C 441. Again, the higher replacement levels resulted in less length change.

Buck (1988) studied a single Class C fly ash, tested according to C 441 at replacements up to 65 percent. The maximum reduction in expansion occurred at 60 percent. The performance at 65 percent was very much like that at 30 percent replacement, which was still considerably better than performance than with no fly ash.

In work involving large amounts of Class F fly ash (>50 percent) at very low w/c's (<0.35) and high-alkali cement, Malhotra (1990) and Alasali and Malhotra (1991) found considerable improvement in performance relative to controls. Standard test methods plus some novel test methods were used. Expansions of fly ash mixtures were consistently below 0.02 percent at 112 and 275 days, respectively.

Resistance to Chloride-Ion Penetration

Only one reference to the rapid chloride pentration test (AASHTO T 227-831) was found. Malhotra (1990) reported test results for several low-calcium fly ash mixtures (58 percent, by mass) made at very low w/c's (0.31). There was a strong age-dependent effect. Values between 3,000 and 10,000 coulombs were reported at 7 days. These fell to between 200 and 1,000 coulombs by 91 days. The current standard method is ASTM C 1202.

5 Research Needed

The effect of carbon in fly ash on demand for air-entraining admixture (AEA) has been well worked out for conventional levels of pozzolan. Air can be entrained in concrete using fly ash at almost any level of loss on ignition (being taken as a measure of carbon content) if the fly ash is uniform in this property. It is the variation in AEA demand that is problematic when high and variable values for loss on ignition are encountered in the fly ash. It is generally believed that variation in AEA demand is minor when values for loss on ignition are less than or equal to 6 percent, but that variation problems occur for materials with variable loss on ignition at average levels greater than 6 percent. There was no literature found that verified this generality for high-fly ash concretes.

Time of setting of concretes containing large amounts of Class C fly ash needs to be explored in more detail. Some fly ashes appear to be very active in affecting time of setting, but little is known about how common this phenomenon is and whether or not it can be predicted from standard tests done on fly ash. Additional test methods may need to be used. A specification requirement for the effect of fly ash on time of setting probably needs to be developed. Ideally, such a requirement should be based on a test method that is applied to the fly ash only. Some fly ash tests are based on test methods that measure the performance of a fly ash-cement mixture. This type of test should be avoided, if possible, because cement properties are not invariant. Results can vary considerably, depending on the cement chosen for the test procedure.

Very little work was found on the curing requirement for high fly ash concrete, but that found clearly indicated that large amounts of fly ash resulted in the need for longer curing to achieve equivalent strengths. A program needs to be pursued that investigates the effects of various lengths of early curing on strength development. Other variables that should be included in this study would be w/c, type of fly ash, total cementitious materials content, and type of curing (100 percent RH vs soaking). Philleo [unpublished comments] expressed concern that type of curing may be important in affecting strength development, particularly in low w/c mixtures.

Research needs to be conducted that would support the development of heat-of-hydration specification requirements that need to be applied to cement

when pozzolan is intended to be used as a partial replacement in the mixture design. This may require development of a pozzolan specification or a specification for the cement-pozzolan blend intended to be used.

The literature on the durability of high fly ash concretes is relatively small, but there was no strong indication that unexpected problems develop at high fly ash levels. Permeability, which is often taken as a property that relates to certain types of durability, needs to be described in relation to fly ash content and extent of curing.

In developing a procedure by which one can identify optimum levels of fly ash for a given set of starting materials, it is important to have identified a set of materials properties that are both measurable and relate strongly to performance. Many of the properties currently measured as part of routine testing of fly ash do not strongly reflect performance (Butler 1983, Mehta 1985). Two sets of data have been published (Mehta 1985); Sivasundaram, Carette, and Malhotra (1990) that include considerable information on physical properties of fly ash and performance properties in concrete. These could be analyzed further using multivariate statistical procedures to identify useful measures of performance properties.

Adequate guidance on procedures by which one identifies the optimum amount of fly ash that can be used has not been developed. It would be desirable to develop a set of procedures based on small specimens (paste and/or mortar) that would allow a description of performance for various levels of fly ash that could be expected in concretes. Mortar or paste tests are considerably cheaper to execute than concrete tests. The disadvantage with these tests is that they often do not give an exact measure of concrete properties, although they usually do correlate reasonably well with concrete properties. An optimization procedure will probably always contain a requirement for concrete testing for purposes of calibration. The objective of a procedure development would be to determine the minimum number of concrete tests that would be necessary to calibrate mortar or paste tests.

6 Conclusions

The preponderance of evidence indicates that fly ash contents considerably higher than currently in use are reasonable for most concrete applications. Research is needed in some areas, such as time of setting, curing, heat of hydration, and mixture proportioning procedures that identify optimum fly ash contents.

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This report reviews some of the literature pertaining to the use of large amounts of fly ash in concrete. Summaries of experience with high fly ash concrete are presented, both as reported from laboratory studies and from published summaries of experience in construction. Areas in which increased research is necessary are identified.

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